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Performance Results from a Cold Climate Case Study for Affordable Zero Energy Homes

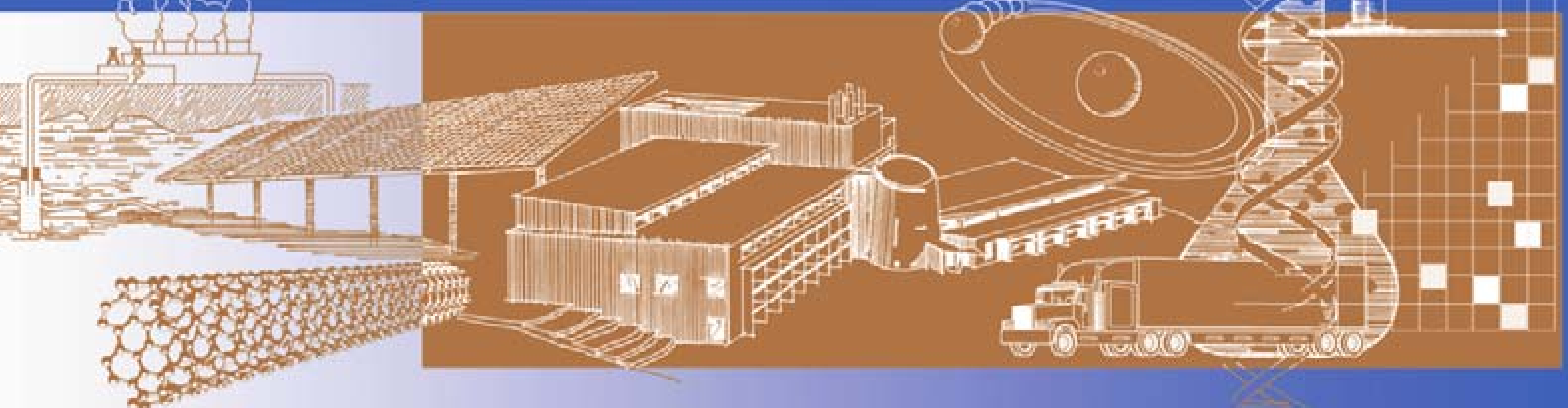
Preprint

P. Norton and C. Christensen

To be presented at the ASHRAE Winter Conference
New York, New York
January 19–23, 2008

Conference Paper
NREL/CP-550-42339
November 2007

NREL is operated by Midwest Research Institute ● Battelle   Contract No. DE-AC36-99-GO10337



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Performance Results from a Cold Climate Case Study for Affordable Zero Energy Homes

ABSTRACT

The design of this 1280 square foot, 3-bedroom Denver zero energy home (ZEH) carefully combines envelope efficiency, efficient equipment, appliances and lighting, a photovoltaic (PV) system, and passive and active solar thermal features to exceed the net zero energy goal. In January, 2006 a data acquisition system was installed in the home to monitor its performance over the course of a year. This paper presents full year of energy performance data on the home.

From April 2006 through March 2007 the home's 4kW PV system produced 5127 kWh of AC electricity. Only 3585 kWh of electricity and 57 therms of natural gas were used in the home during this period. On a source energy basis, the home produced 24% more energy than it used. The energy used for space heating, water heating, and lighting have been dramatically reduced through superinsulation, passive solar tempering, solar water heating, compact florescent lights and other efficiency measures. The energy used in the home is now dominated by appliance and plug loads determined by occupant choices and behavior. These loads constitute 58% of all the source energy used in the home. Because these loads are generally outside of the control of the home designer and vary considerably with different occupants, sizing a PV system to achieve zero net energy performance is challenging.

This case study demonstrates that it is possible to build efficient affordable zero energy homes in cold climates with standard building techniques and materials, simple mechanical systems, and off-the-shelf equipment.

INTRODUCTION

How clean is clean enough? How efficient is efficient enough? These will be among the defining questions of the 21st century. As the human population pushes beyond 6.5 billion on the way to 9.2 billion by 2050 (UNPD 2007) we are faced with increasing environmental consequences …. mass species extinction, toxic air, water, and land pollution, and global warming to name a few. Many of these consequences are related to our energy use and choices. It is clear that we will need to reduce our per capita environmental impact at least in relation to our population growth (and likely beyond) if we wish to stabilize or reduce environmental degradation.

Homes account for 37% of all U.S. electricity consumption and 22% of all U.S. primary energy consumption (EIA 2005). This represents a huge opportunity to reduce our energy consumption and make cleaner choices for the energy we consume. The U.S. Department of Energy's Building America (BA) program is working to increase the energy efficiency of new and existing homes while increasing comfort, and durability and reducing resource use. As part of this program we pursue opportunities to research highly efficient homes with the goal of understanding what works, what doesn't work, and what are the most economic ways to reach very high efficiency targets. The program aims to create cost neutral zero energy homes by 2020. In pursuit of this goal, this home and other research homes around the country designed to approach or achieve the zero energy goal are being built and studied.

The zero energy home (ZEH) presented here was a result of collaboration between the National Renewable Energy Laboratory (NREL) and Habitat for Humanity of Metro Denver. A previous paper details the construction of the home (Norton and Christensen 2006). This paper will briefly review the design then focus on the first year energy performance of the home.

In general, a zero energy home is designed to produce as much energy as it consumes over the course of a full year. The BA program definition is more specific: A zero energy home is designed to offset as much source energy as it consumes over a typical year (based on TMY2 data) using BA Benchmark assumptions for typical occupant behavior. To achieve zero energy the home exchanges energy with the utility power grid. It delivers energy to the grid when the photovoltaic (PV) system is producing more energy than is being used in the home and draws from the grid when the PV system is producing less energy than needed in the home. This project is a case study in reaching the zero energy goal within the affordable housing sector in cold climates. Zero energy is especially important in this sector where increasing energy cost can take a high toll on homeowners with limited economic resources. A zero energy home guarantees long term energy cost stability for the homeowner.

HOME DESIGN

The home, shown in Figure 1, was designed using an early version of the BEOpt building optimization software (Christensen, et. al. 2006) with additional analysis using DOE-2 (LBNL 2004) and TRNSYS (Klein, et. al. 1996) separately. This engineering approach was tempered by regular discussions with Habitat construction staff and volunteers. These discussions weighed the applicability of the optimized solutions to the special needs and economics of a Habitat house – moving the design towards simple, easily maintained mechanical systems and volunteer-friendly construction techniques. We chose solutions that avoided interconnected equipment with complex control systems. The home specifications are summarized in Table 1. Further details on the design process and the final design of the home are presented in an earlier paper (Norton and Christensen 2006).

Figure 1. The NREL/Habitat zero energy home

Table 1. Summary of NREL/Habitat ZEH Attributes

Square footage	1280 sq. ft.
Number of bedrooms	3
Number of occupants	3
Design heating load	15,000 Btu/hr
Walls	Double stud wall Fiberglass batt insulation Nominal R-value = 40 hr ft^2 F/Btu
Ceiling	2-foot raised heel trusses Blown-in fiberglass insulation Nominal R-value = 60 hr ft^2 F/Btu
Floor	Fiberglass batt insulation Nominal R-value = 30 hr ft^2 F/Btu
South windows	Low-e, high SHGC U = 0.30 Btu/hr ft^2 F, SHGC = 0.58
North, west, and east windows	Low-e heat mirror U = 0.23 Btu/hr ft^2 F, SHGC = 0.27
Solar tempered	96 ft^2 of south facing windows 3 ft overhangs for summer shading
Water heating	Drainback solar system 96 ft^2 collectors with 200 gallon storage tank Natural gas tankless water heater for backup
Ventilation	Energy recovery ventilation system with ECMs
Space heating	Direct vent ductless natural gas heater in living room Electric baseboard heaters (750W each) in bedrooms
Lighting	Compact fluorescent throughout the house
Appliances	ENERGY STAR clothes washer and refrigerator
Solar electric	Nominal 4 kW$_p$ DC photovoltaic system
Other features	All mechanical equipment is within conditioned space Light colored roof shingles Increased attic ventilation

The envelope of the home is a double stud wall design with the outer load-bearing walls of the home constructed of 2x4's on 16" centers. On the inside of the load-bearing wall is a second wall of 2x4's on 24" centers. There is a 3 ½" gap between these two stud walls. The finished double stud wall construction allows for three layers of R-13 fiberglass batts: two laid vertically in the cavities of the outer and inner stud walls and a third stacked horizontally between them. This leads to a nominal R-40 wall with very few thermal breaks since the studs do not continue through the entire wall thickness. Two foot raised heel trusses were used to accommodate R-60 blown-in fiberglass insulation. Fiberglass batts rated R-30 were used in the floor. All mechanical equipment is contained within this thermal envelope. The crawlspace is vented and uninsulated. An energy recovery ventilation system is used to supply fresh air to the home. Ducting for the ventilation system is contained in a drop ceiling in the hallway.

The home is designed with large southern glazing for solar gain. The southern windows are double-glazed low-e with a "high"SHGC of 0.58. Three foot overhangs provide window shading when solar gain is not needed. Double-glazed, low-emissivity, low solar heat gain coefficient (SHGC) windows were used on the north, east, and west of the home.

With these shell efficiency features, the peak design heating load for the home is very small – about 15,000 Btu/hr (4.4 kW). This load was met using a single point sealed combustion furnace located in the living room and small (750 Watt) electric resistance baseboard heaters in the bedrooms. Heat distribution is enhanced by the energy recovery ventilation system that pulls stale air from the kitchen and bathroom and delivers fresh air to the living room and each bedroom. Water heating is accomplished using a solar thermal system with a natural gas tankless heater for back-up. The solar system has 96 sq. ft of collector area and 200 gallons of water for thermal storage. The system is sized to provide a high solar saving fraction year round, and a drainback configuration is used to avoid potential glycol overheating problems during summer stagnation. Active solar space heating is not used to keep the system simple and because the combination of passive solar and superinsulation are already predicted to meet the space heating loads on sunny winter days.

DATA ACQUISITION SYSTEM DESIGN

A data acquisition system was installed to determine if the home met its energy design goal of zero energy. The system was designed to allow disaggregation of the PV energy production and some end uses. A summary of the data collected and the equipment used is given in Table 2.

Table 2. Measurements and Components of the Data Acquisition System

Measurements	Component
Electrical energy measurements	
PV energy production Baseboard electric heaters Hard-wired lights Kitchen range Ventilation system Solar pump Space and water heating controls All other loads	Pulse output watt-hour transducers
Natural gas measurements	
Space heater Back-up water heater	Diaphragm gas meters with pulse output
Indoor and water temperatures	
Living room North bedroom Southeast bedroom Cold water supply Solar tank Solar - water to collectors Solar - water from collectors Solar - water to back-up heater Hot water supply to house	Type T thermocouples
Water flow	
Hot water use	Water Meter
Weather related measurements	
Outdoor temperature and RH	T&RH sensor w/shield
Solar radiation - horizontal	Pyranometer
Solar radiation - plane of collectors	Pyranometer
Data Logging Equipment	
	Logger
	Thermocouple multiplexer
	Switch closure multiplexer
Communications	
	Cell phone modem

Data were collected on 1-minute and 1-hour intervals. Most of the analysis of the home performance was done using the 1-hour data. The 1-minute data was used for troubleshooting and for investigating transient behavior of the solar water heating system. An Excel spreadsheet using array formulas was created to aggregate daily and monthly averages and sums and to create graphics on the performance of the home. All electrical end use measurements were in place by February 2006. However, the water flow and natural gas end use monitoring was not complete until April 2006. **Unless otherwise stated, all annual figures in this report include the period from April 2006 through March 2007**.

HOME ENERGY PERFORMANCE

The home is located in Wheat Ridge, Colorado which is part of the Denver metropolotian area. Wheat Ridge has 5988 heating degree days (65^{o}F base) and 496 cooling degree days (65^{o}F base) (NOAA 2007). We measured a total of 1607 full sun hours during the 12 month monitoring period. The home received a Colorado E-star rating of 95.

The home's net source energy performance exceeded expectations. The PV system was sized to achieve net zero annual source energy using TMY2 weather data for Boulder, Colorado (Marion and Urban 1995) and BA Benchmark assumptions for occupant effects such as temperature setpoints and miscellaneous energy use (Hendron, et. al. 2004). The BA Benchmark represents U.S. average occupancy choices and behavior. It turns out that the owner/occupants of the NREL/Habitat ZEH use less energy than the BA Benchmark occupants average energy users. Therefore the home performed beyond zero and was a net source energy producer. A summary of the overall home performance is given in Table 3.

Table 3. 12 Month Performance Summary of NREL/Habitat ZEH

	kWh	MBtu
Site Energy Summary		
Total site electricity consumption	3585	12
Total AC site PV electricity production	5127	17
Net site electricity production	1543	5.3
Total site natural gas consumption	1665	5.7
Source Energy Summary*		
Total source energy consumption	13025	44
Total source energy offset	16201	55
Net source energy offset	3176	11
Percent of source energy consumption offset via on site renewable production	**124%**	**124%**

* The site to source energy conversions are U.S. national averages according to the BA Analysis Procedures (Hendron, et. al. 2004): site-to-source multiplier for electricity = 3.16; site-to-source multiplier for natural gas = 1.02

The monthly site electricity and natural gas consumption by end uses are shown in Figures 2 and 3. The monthly source energy consumption by end use is shown in Figure 4. These figures are consumption only – they do not include the electricity generated by the PV system. Rather than being separately monitored for the entire year, the average refrigerator energy use over an 84 day period was measured and applied to each day of the year.

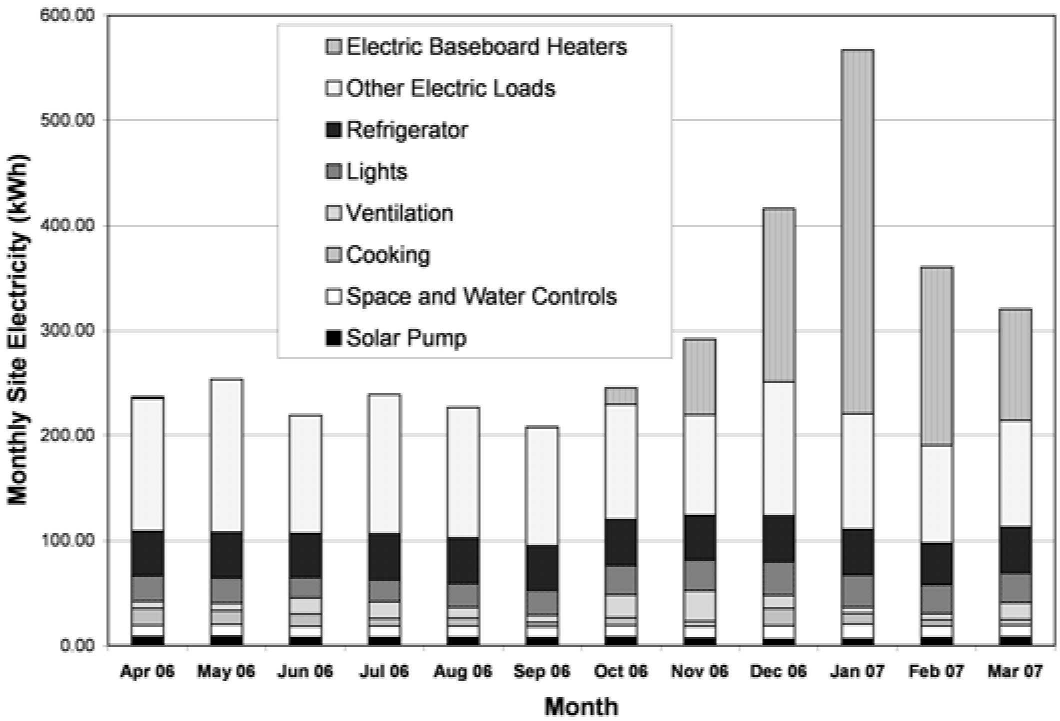

Figure 2. Monthly site electricity consumption by end use

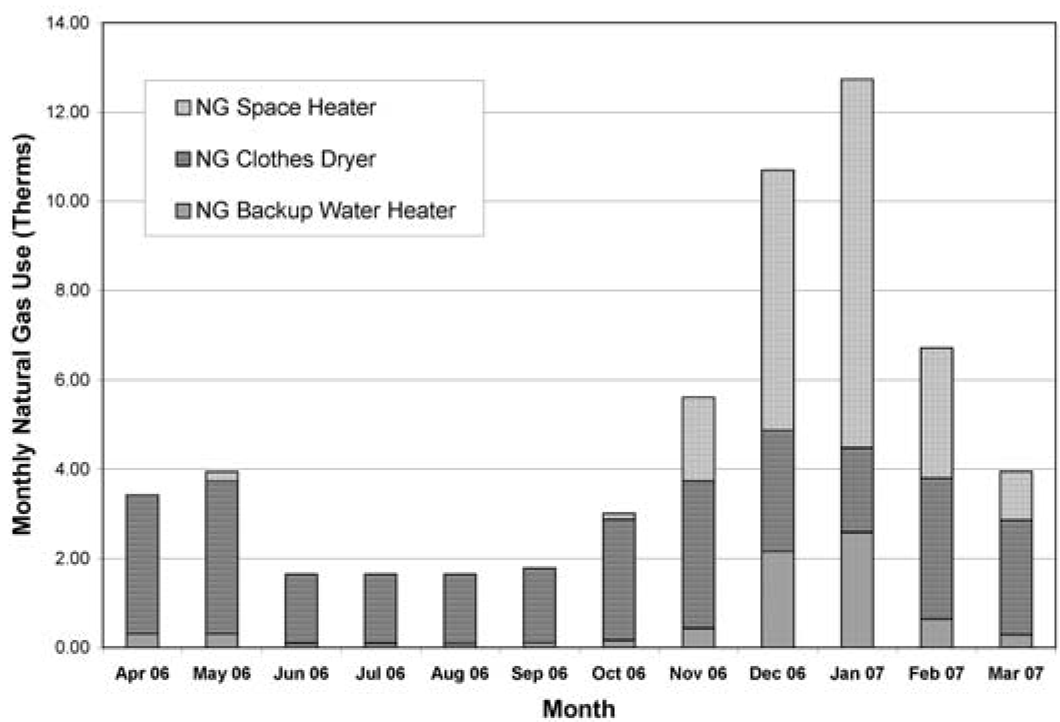

Figure 3. Monthly site natural gas consumption by end use

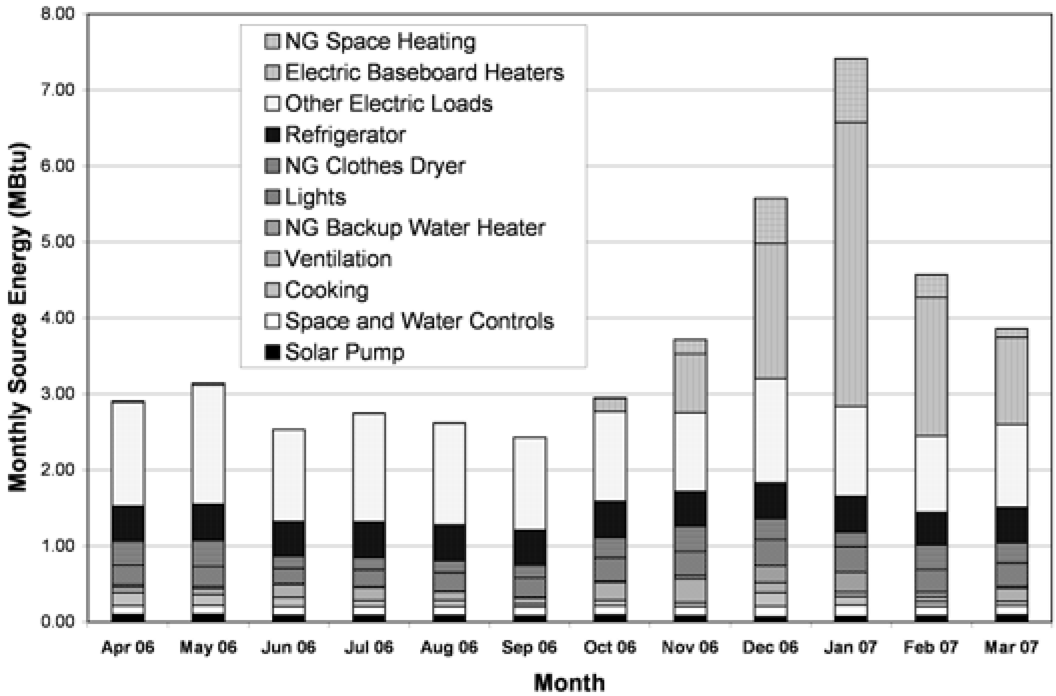

Figure 4. Monthly source energy consumption by end use

The ventilation energy use in the home was lower than expected. When we investigated we found that the adjustment for the continuous ventilation rate installed in the mechanical room actually turned off the ventilation system when set to the "low" setting. The ventilation system was often off during the year of monitoring. Therefore the home was underventilated during this time and the heating load was reduced somewhat. Much of the monitoried ventilation data represents only the standby power draw. The homeowner was informed of this issue so she can maintain proper ventilation. A stop on the adjustment that maintains the minimum ventilation rate at ASHRAE 62.2 recommendations would solve the problem in future installations.

As expected, space heating is the largest electricity, natural gas and source energy consumer in the winter months. In the design phase of the project we assumed the natural gas heater in the living room would provide the bulk of the home heating. This assumption was based on conversations with builders who had built similarly sized double stud wall homes in colder climates and used point source heating with favorable results. The natural gas heater was sized to meet the entire design heating load. The baseboard heaters were seen as back-up to the natural gas heater if the distribution of the heat to the bedrooms was inadaquate. However, in reality the baseboard electric heaters accounted for 60% of the total space heating site energy and 82% of the total space heating source energy. This indicates the heat distribution to the bedrooms from the natual gas heater was not adequate. For the house to rely more on natural gas for heating, additional natural gas heaters or a heat distribution system would be needed.

Despite submetering of most large end uses, the "other electric loads" was the largest single year-round end use category. The annual average power draw of the other electrical loads is about 164 Watts. Nearly half of this power draw (84 W) varies hour-by-hour with peaks in the morning before the occupants leave for school or work and in the evening when they return but before they retire for the day. The remaining 80 W is drawn continuously, day and night, with occupants in the house or not. We investigated these base electric loads using plug-in energy meters capable of measuring energy draws over 5 W. The results are given in Table 4. The measured end uses account for about half of the baseline electric loads. Some hardwired end uses that may contribute to the remaining half include ground fault interrupters (GFI), doorbell transformer, smoke alarms, and our data acquision system (estimated to be about 7 to 9 Watts).

Table 4. Measure Baseline Electric Loads

End Use	Power Consumption (W)
Entertainment center stand-by*	26
Additional TV	6
Computer, monitor, printer stand-by	5
Digital clock (rated power draw)	3
Microwave oven stand-by	0 (<5)
Clothes washer stand-by	0 (<5)
Clothes dryer stand-by	0 (<5)
Totals	**40**

* includes TV, stereo, cordless phone, DVD player, and digital clock

The annual source energy by end use is given in Table 5. Other electric loads are the largest energy use category. Generally speaking, the end uses within the control of the building designer include the space conditioning, water heating, ventilation, and lighting. If we sum all other loads (often referred to as "appliance and plug loads") they account for 58% of the total source energy consumption. These loads are primarily the result of occupant choices and behavior. They vary substantially with homeowner and time. This presents a challenge for ZEH home designers. The PV system output must be sized to match all energy consumption to reach the ZEH goal but the energy consumption is dominated by loads that are out of the designers control, vary substantially with different homeowners, and are unknowable in advance for a spec home.

Table 5. Annual Source Energy by End Use

End use	Annual Source Energy (MBtu)	Annual Source Energy (kWh)	Percent of Total
Other electric loads	15.5	4,550	34%
Electric baseboard heaters	9.2	2,690	21%
Refrigerator	5.6	1,630	13%
Lights	3.3	970	7%
Natural gas clothes dryer	2.8	830	6%
Natural gas space heating	2.0	590	5%
Ventilation	1.6	460	4%
Space and water controls	1.5	420	3%
Cooking	1.3	370	3%
Solar pump	1.0	300	2%
Natural gas backup water heating	0.7	220	2%
Totals	**44.5**	**13,030**	**100%**

PV Production

A free PV performance calculator, called PVWatts, is available on NREL's Renewable Resource Data Center website (http://rredc.nrel.gov). The PVWatts simulation of the 4 kW_p DC PV system using TMY2 weather data from Boulder, Colorado predicts the system will deliver 5756 kWh (19.6 MBtu) of AC electricity per year with no shading. The PVWatts default derate factor of 0.77 was used for this prediction. A shading analysis indicated a 15% loss of solar radiation due to shading from mature trees on the site reducing the expected annual PV production to 4,892 kWh (16.7 MBtu) The actual energy delivered was 5127 kWh (17 MBtu), exceeding the prediction by 5%. The production exceeded prediction despite the fact that the measured total horizontal radiation was about 4% lower than that in the TMY2 data and the PV system was covered in snow and produced no electricity for 35 days during the unusually snowy weather in Denver in December 2006 and January 2007. This indicates that the PVWatts default derate factor may be conservative or that the shading analysis overestimated the impact of the shading.

The daily and cumulative net electricity use is shown in Figure 5. The PV system produces more electricity than was used in the home nearly every day throughout the spring, summer, and fall. Despite the long period of net use with no production in January 2007, the home completed the 12 month period with a net production of 1,543 kWh (5.3 MBtu).

We calculated a simple monthly average PV system efficiency by dividing the monthly total AC electricity production by the monthly total solar radiation on the plane of the collectors times the area of the collectors. The monthly average efficiency varied from a low of 2.1% in January 2007 when the collectors were snow covered for many days, to a high of 13.1% in November 2006. The annual average efficiency was 10.2%.

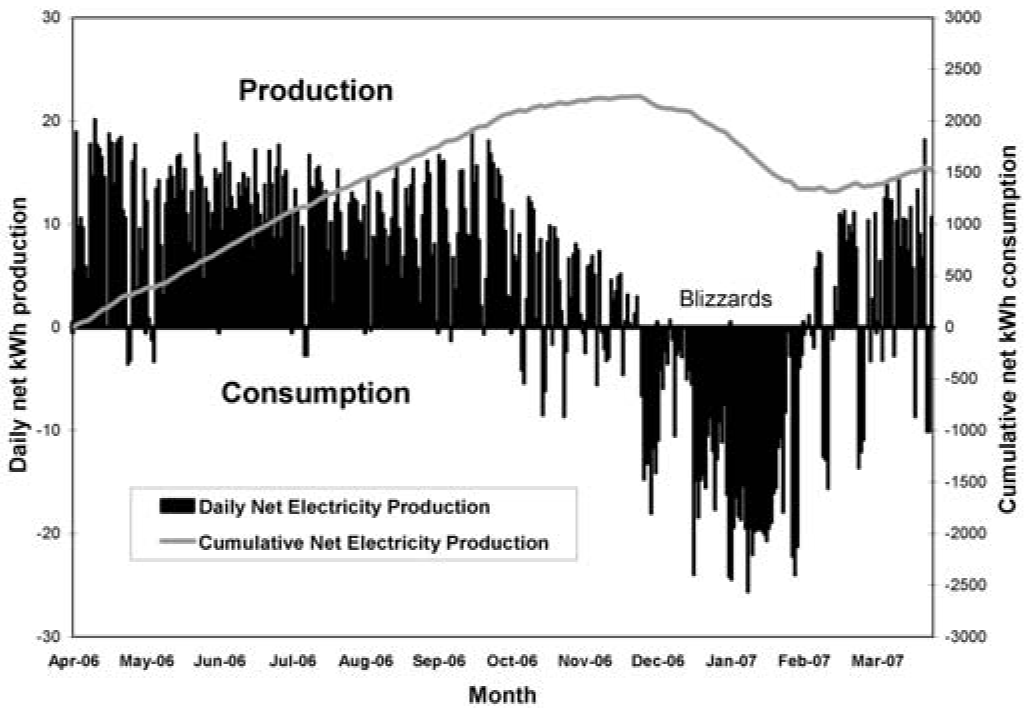

Figure 5. Daily and cumulative net site electricity use

Solar Water Heating

We developed design expectations for the solar water heating system using TRNSYS modeling software. We used the model to investigate tradeoffs with tilt angle, collector size, and storage tank size. The initial BEopt results indicated an investment in a high savings fraction system was justified. The final design incorporated a drainback system with 96 ft^2 (8.9 m^2) collector lying directly on the roof (tilt angle = 27 degrees), with 200 gallons (757 liters) of water for thermal storage.

Energy delivered to the back-up water heater by the solar system was tracked by measuring the water temperature entering the solar tank heat exchanger, the water temperature entering the back-up water heater from the solar tank heat exchanger, and the water flow rate. The flow*ΔT calculation is performed continuously by the data logger and stored on a 1 minute basis. We also logged the electricity used by the solar pump and the natural gas used by the tankless back-up water heater. Using this information we have defined three solar savings fractions:

1. Thermal site solar savings fraction = Q_s /(Q_s + Q_{ng})
2. Total site solar savings fraction = (Q_s - E_p)/ Q_s + Q_{ng})
3. Total source solar savings fraction = (Q_s -($E_pM_{e)}$))/((Q_s + $Q_{ng}M_g$))

Where:
Q_s = Thermal energy delivered by the solar system to the back-up water heater
Q_{ng} = Energy content of the natural gas consumed by the back-up water heater
E_p = Electrical energy used by the solar pump
M_e = 3.16 = site to source multiplier for electricity (Hendron, et. al. 2004)
M_g = 1.02 = site to source multiplier for natural gas (Hendron, et. al. 2004)

Table 6 lists the annual predicted and measured performance characteristics of the solar thermal system.

Table 6. Annual Predicted and Measured Performance of the Solar Water Heating System

	Predicted	Measured	Percent Difference
Average daily hot water use	63.4 gallons	20.5 gallons	-68%
Delivered energy	12.29 MBtu (3,602kWh)	2.21 MBtu (647 kWh)	-82%
Pump energy	0.638 MBtu (187 kWh)	0.321 MBtu (94 kWh)	-50%
Ratio of pump energy to delivered energy	0.052	0.145	179%
Maximum monthly thermal site solar saving fraction	1.00	0.95	-5%
Annual thermal site solar savings fraction	0.92	0.75	-18%
Annual total site solar savings fraction	0.88	0.64	-27%
Annual total source solar savings fraction	0.78	0.40	-49%

The delivered energy of the solar water heater was a small fraction of the predicted value. The main reason for this appears to be the fact that the occupants used less than a third of the predicted average daily hot water. The prediction is based on the BA Benchmark which represents national average hot water use. Although the thermal site solar savings fraction was nearly unity during the summer months, the delivered energy was small due to small hot water demand. Because of the low delivered energy, the pump energy becomes more significant and the total site solar savings fraction was only 0.66 compared to the prediction of 0.88. On a source energy basis the savings fraction drops to 0.39 because of the site-to-source multiplier for the electricity used by the pump.

We calculated a simple overall system efficiency for the solar water heater by dividing the thermal energy delivered from the solar tank to the back-up water heater by the total solar radiation on the plane of the collectors times the area of the collectors. The monthly average efficiency varied from 2.8% in August to 7.4% in December. The annual average efficiency was 4.8%.

The low delivered energy of the solar thermal system throws into question whether the investment is justified. The installed cost of the solar thermal system was $7,068.00. The tankless back-up water heater cost $1,340.00 plus installation (the cost of installation is not available). We used measured PV and solar water heating data to pose the following question: "What would it cost to increase the size of the PV system and use an electric tank heater?" Conventional wisdom hold that the solar water heating system is a better investment. A comparison of the two systems is shown in Table 7. For both cases, all source energy use is displaced by the solar systems.

Table 7. Comparison of Thermal and PV Solar Water Heating Systems based on measured data from April 2006 through March 2007

	Thermal **Solar Water Heating System** with **Tankless Back-up** (EF = 0.84) and PV to **Displace Natural Gas Use**	Incremental PV with an **Electric Tank Water Back-up Heater** (EF=.95)
Site energy from solar system	2.21 MBtu (647 kWh)	0
Site pump energy	0.321 MBtu (94 kWh)	0
Site energy to water heater	0.727 MBtu(213 kWh)	2.97 MBtu (870 kWh)
PV energy needed [1]	0.549 MBtu (161 kWh)	2.97 MBtu (870 kWh)
PV needed (W_p) [2]	125	672
Solar water heater installed cost	$7,068	n/a
Conventional water heater cost [3]	$1,340	$400
Incremental PV installed cost [4]	$881	$4,702
Total system cost estimate	$9,289	$5,102

[1] For solar water heater case, this includes the pump energy plus the PV energy required to displace the source energy from the water heater (= 94 kWh + 213/3.16 kWh)
[2] Annual PV production was 1.295 kWh per rated peak watt of the PV system
[3] Installation costs for the conventional systems are not included
[4] In both cases we assume that the balance of system investments such as inverter, combiner box and disconnects have already been made and the full retail installed incremental cost for PV of $7.00/W_p$.

This analysis is dependent on specific system costs as well as the actual 12 months of weather, hot water use and NREL/Habitat ZEH solar water heater system performance upon which it is based. If the low hot water use of the household was known in advance, a smaller solar water heating system could have been installed at lower cost. PV costs would be higher if an additional inverter were needed. Cost rebates, not considered in this analysis, vary considerably around the country. Colorado currently has a rebate of up to $4.50/W_p$ for PV. The size of the PV in the incremental PV option could be reduced by using a heat pump water heater in place of the conventional electric tank heater. The only conclusion that can be drawn from this simple analysis is that the conventional wisdom may not be true in all cases and additional investigation into the comparison of solar water heating and PV investments may be warranted.

Utility Bills

Zero energy performance does not necessarily equate to zero utility bills. The NREL/Habitat ZEH was designed to use natural gas for space heating, backup water heating, and clothes drying and produce and excess of PV electricity to offset the natural gas source energy use. The Xcel Energy net metering arrangement calls for any excess energy accumulated by the end of the calendar year to be zeroed-out and compensated for at the "average hourly incremental cost of electricity supply over the most recent calendar year" (Xcel Energy 2006). In a heating dominated climate, a ZEH produces more energy than it consumes in the summer when daylight hours are long and consumes more energy than it produces in the winter when daylight hours are shorter and energy is consumed for space heating. Because the accumulated excess energy is zeroed-out in the winter when PV production is low, the homeowner will likely have to pay for net electricity consumption in January and February. Because the cost of production is less than the retail cost of the electricity, the compensation the homeowner receives for the excess energy accumulated by December 31 will be less than the cost of the net electricity used in February and March. A more ideal time (for the homeowner) to zero-out the accumulated net production would be near the spring equinox when the accumulation would be closest to zero. In addition to charges for energy use, utility bills include fixed monthly charges for electricity and natural gas. In the design phase of the project we used simulated energy performance to estimate a monthly average utility bill of $30.00 for the house under the current Xcel rate structure.

As energy use is reduced, fixed charges become a larger portion of the utility bill. For the NREL/Habitat ZEH, there was no use charge for electricity most months due to net production rather than consumption but the fixed charge for electricity still applied. The monthly natural gas bill included both fixed and fuel use charges.

Some billing problems occurred with the house – probably because it was one of the first net metered house under Colorado's renewable portfolio Amendment 37. The home began with an analog meter that ran backwards as the PV produced more electricity than was consumed in the house. The first bill was not received until the home had been occupied for 4 months. When it arrived, the meter reading was interpreted as indicating a large positive number rather than a small negative number and the occupant received a $939.68 electricity charge on her first bill! Billing continued to be somewhat erratic throughout the first year. An additional hitch came when the analog meter was replaced by a digital net meter. An incorrect final analog meter reading was later corrected. Rather than zeroing-out the accumulated net positive electricity at the end of December, it was zeroed-out when the analog meter was replaced on November 8, 2006. At this time the home had generated 2517 kWh more than it had consumed since the meter was installed in October 2005. The homeowner was reimbursed for this excess generation at a rate of $.04291/kWh. In January 2006 she received a check from Xcel energy for $108.00.

The actual total annual and average monthly electricity and natural gas costs are given in Table 8. The average total utility bill was about $17/month.

Table 8. Total Annual and Average Monthly Utility Bills for the Monitored Period

	Fixed Charge	Use Charge	Total
Total annual electricity	$94.69	$69.58	$164.27
Reimbursement for net production		-$108.00	-$108.00
Total annual natural gas	$106.43	$43.03	$149.46
Total annual bill	$201.12	$4.61	$205.73
Average monthly electricity	$7.89	$5.80	$13.68
Reimbursement for net production		-$9.00	-$9.00
Average monthly natural gas	$8.86	$3.58	$12.46
Average monthly total utility bill	$16.75	$0.38	$17.14

COMPARING PERFORMANCE TO EXPECTATIONS BASED ON SIMULATIONS

The final design energy simulation of the building was done with DOE-2 software. This simulation uses assumptions for set-points, appliance and plug loads, lighting and plug load schedules, and hot water use based on the Building America Performance Analysis Procedures. The simulation is driven by TMY2 weather data. After collecting a year of monitored data, we re-ran the simulation leaving the building and equipment models unchanged but driving the simulation with measured weather and occupant effects. The changes made to "tune" the model to actual weather and occupants are listed below:

- Hot water used was reduced to 20.4 gal/day. (BA assumption = 65.6 gal/day)
- Appliance and plug loads were reduced to a total of 2079 kWh/year.(BA assumption = 3053 kWh/yr)
- Dryer energy use was reduced to 28 therms/yr. (BA assumption = of 76 therms/yr)
- Cooking was changed from natural gas (which was originally anticipated) to electric (which was actually installed).
- Base lighting kWh adjusted down by 30% and impact of compact fluorescent increased from 60% reduction to 75% reduction based on measured data.
- Lighting schedule adjusted based on monitored data.
- Plug load and miscellaneous electric use schedule adjusted based on monitored data.
- Hot water usage schedule adjusted based on monitored data.
- Thermostat settings were adjusted based on monitored data.
- Monthly PV adjusted to monitored values (from 5274 kWh/yr to 5127 kWh/yr).
- Ventilation energy lowered from 298 kWh/yr to 144 kWh/yr.
- Solar DHW effectiveness adjusted to 80% solar savings fraction annually.

The monthly electricity and natural gas consumption predicted by the original simulation and the tuned simulation is shown with the measured data in Figures 6 and 7.

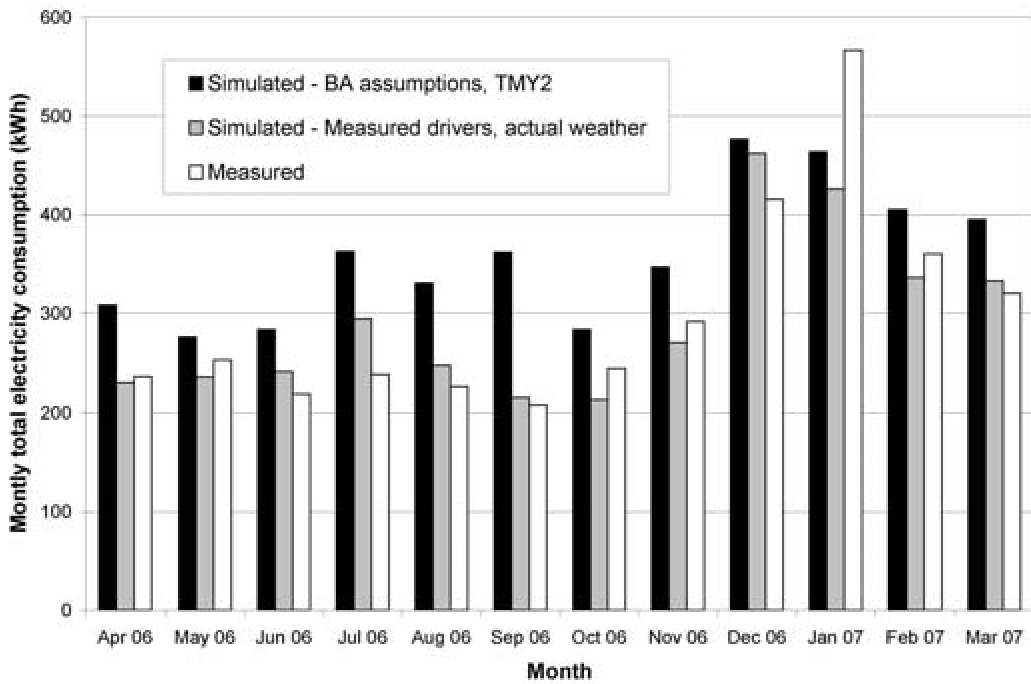

Figure 6. Simulated and measured monthly electricity consumption

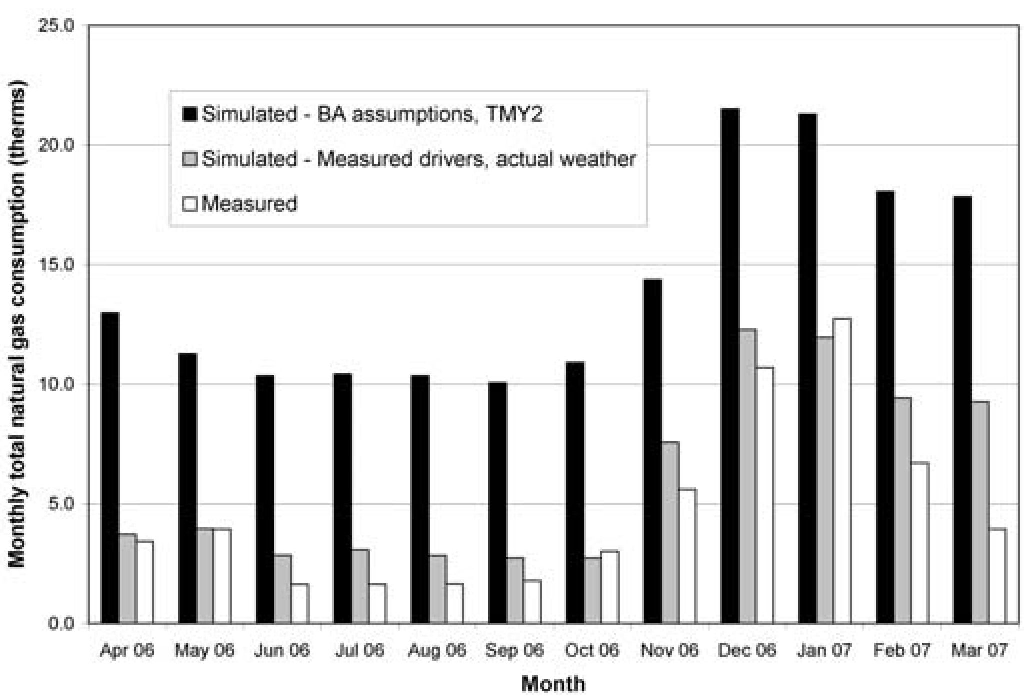

Figure 7. Simulated and measured monthly natural gas consumption

The simulation using BA assumptions and TMY2 weather overestimated the annual electricity consumption by 19%. However when the simulation used measured occupant and weather drivers, it agreed with the measured data on annual electricity consumption to within 3%.

The simulation using BA assumptions and TMY2 weather overestimated the annual natural gas consumption by over 200%. The simulation overestimated all natural gas end uses: clothes drying, backup water heating and space heating. In the tuned simulation, the clothes drying gas use and the hot water use were set to the measured value. The measured annual average solar saving fraction was used to simulate backup water heater gas consumption. Measured room temperatures were used to generate more representative thermostat settings in the simulation. With these changes, the difference between simulated and measured natural gas consumption is reduced to only 17 therms. Because the natural gas consumption of the home is small, this still represents a 32% difference between tuned simulation and measurement. The simulation still overpredicts the space heating natural gas consumption in the coldest months. This difference is probably due to imperfect modeling of the natural gas heater and remaining differences between simulated and actual daily temperature setpoints.

When natural gas and electricity are combined, the tuned simulation is within 8% of the measured annual energy consumption.

We used the simulation with BA assumptions and TMY2 weather along with Colorado state carbon dioxide emissions factors to estimate the carbon dioxide emissions associated with the energy use in the home. The annual emissions associated with the Habitat/NREL ZEH with BA Benchmark occupants would be only 0.24 metric tons of carbon dioxide equivalent. Using the same assumptions, the carbon dioxide emissions of a Habitat for Humanity of Metro Denver standard practice home (which is built to ENERGYSTAR standards) would be 9.3 metric tons of carbon dioxide equivalent annually. To put these numbers in perspective, the average annual U.S. household carbon dioxide emissions are about 18.9 metric tons (EPA, 2007).

DISCUSSION

Installation problems were encountered with the energy recovery ventilation system. In addition to the control problem described previously, some of the ducts were incorrectly connected during the installation. As ERV systems become more common, some ERV commissioning is recommended if the installation contractor is not familiar with these systems.

The a built-in thermostats included with the baseboard heaters proved to be imprecise at best. If we use baseboard electric heaters in future projects we will include a wall-mounted line-voltage thermostat for each heater.

The economics of a zero energy home is a function of the specific net metering tariffs for its location. Some of these tariff structures are more favorable than others. For example, the Tennessee Valley Authority (TVA) buys 100% of the PV generated electricity from home PV systems at $0.15/kWh. The cost of electricity varies with the TVA area. In Oak Ridge, TN the electricity use charge is $0.07543/kWh, so homeowners are paid nearly twice their electricity rate for their PV production. Table 9 shows what the energy costs for the house would be if the Oak Ridge electricity and natural gas rate structure were available in Denver. Rather than having to pay the utilities, the homeowner would have ***received*** an average of $24/month. In locations with incentive programs less favorable than Tennessee's, a ZEH home can be seen as a hedging strategy against uncertainty in future energy prices. Owners of affordable homes generally have less ability to absorb energy price shocks and would therefore benefit from the low and stable home energy costs of zero energy homes.

Table 9. Cost of Energy at the Oak Ridge, TN Rate Structure

	Value	Units	Oak Ridge Cost/Unit	Total Cost
PV reimbursement	5127	kWh	-$0.15	-$769.05
Electricity fixed charge	12	months	$7.46	$89.52
Electricity use charge	3595	kWh	$0.07543	$270.42
Natural gas fixed charge	12	months	$3.50	$42.00
Natural gas use charge	57	Therms	$1.4030	$79.97
Total annual cost				-$287.14
Total average monthly cost				-$23.93

The PV sizing for this project was based on BA Benchmark appliance and plug load use designed to represent national averages. With this sizing strategy, one could expect the home's chances of achieving zero energy performance as 50/50 – half of the occupants will be above average energy consumers and half will be below average. The NREL/Habitat ZEH appliance and plug load energy use was 32% less than the Benchmark level and still accounts for 58% of all energy used in the home. This is one of the main reasons the home exceeded the net zero energy goal and was a net energy producer. Yet the occupant's lifestyle is not one of deprivation for the sake of energy savings. Another sizing strategy that could be adopted would be to size the PV system for an energy conscious user and provide educational material to the occupant that outlines the energy budget to achieve zero energy in the home. An inexpensive whole-house energy meter can be installed in the home for feedback.

It was a design decision to use natural gas in the NREL/Habitat ZEH and displace the gas use with excess PV electricity generation to achieve net zero source energy. The PV system required for this approach is smaller than for an all-electric house with resistive heating thereby reducing overall home cost to achieve net zero source energy with the same societal benefits. However, because the occupants are below average energy users, the net *site* energy use was nearly zero. This means the home could use electric resistance heat to meet the loads currently served by natural gas and still come very close to the zero energy goal without additional PV panels. Eliminating the natural gas would further simplify the mechanical equipment and reduce the already very small utility bill. Making the home all-electric and using the PV sizing strategy described above may be a reasonable approach for cold-climate affordable ZEH.

The person-to-person variability of appliance and plug load energy use makes sizing the PV system for zero energy challenging. One advantage of net metered PV is a 100% utilization factor. If the occupant does not need the energy being provided by the PV it is sent to the grid for others to use. (As shown above, economic compensation for this energy varies considerably.) In contrast, if the homeowner used less hot water than expected, the solar thermal system stagnates at its maximum temperature and cannot take advantage of additional solar resource. In effect, the energy that could have been collected is lost. Because water use is highly variable it presents a similar sizing challenge as the PV system. If the water use is less than expected the savings drop off substantially and the economic value of the system is reduced. For a ZEH that must supply all its energy from renewable resources, the economic value of solar thermal and PV needs to be carefully weighed taking the uncertainty of the occupant effects into account. This is an area that warrants further investigation.

The response to this house has been overwhelming. The home appeared on Fox National News, was visited by Secretary of Energy Samuel Bodman and Congressman Bob Beauprez, and has been written-up in Home Energy Magazine, Energy Design Update, countless web pages, and several local newspaper stories. The home was also on the National Solar Tour in 2005 and received an exemplary building award from the Colorado Renewable Energy Society. Habitat for Humanity of Metro Denver and NREL continue to receive weekly queries on the home. This attention provides better visibility for project sponsors and equipment donors and may equate to more potential sponsors for Habitat. This type of visibility is a benefit to the affordable home builders that should be considered in decisions to pursue super efficient home projects.

CONCLUSIONS

- The NREL/Habitat ZEH exceeded its goal of zero net source energy and was a net energy producer in the first year.
- PV system sizing for zero energy homes is challenging.
- The prediction of total home energy use for a specific house becomes highly uncertain due to individual occupant choices and behavior.
- Meeting the ZEH design goal becomes dependent on occupant behavior.
- The economics of excess annual PV production are dependent on net metering agreements.
- Zero energy does not necessarily mean zero utility bill.
- There are fixed monthly costs for natural gas and electricity service.
- Natural gas *costs* may not be displaced by net electricity production.
- It is possible to make efficient affordable ZEHs with standard construction techniques and off-the-shelf equipment.

ACKNOWLEDGEMENTS

The authors would like to thank the many individuals and organizations that supported this project including: homeowner Amy Whalen; The U.S. Department of Energy's Building Technologies Program; Midwest Research Institute; Battelle; Energy Outreach Colorado; Xcel Energy; The Governors Office of Energy Management and Conservation; Secretary of Energy Samuel Bodman; Congressman Bob Beauprez; Lori Vaclavic, Bruce Carpenter, Andy Blackmun, Brady Nelson, Pandora Reagan, and Lynne Brown of Habitat of Metro Denver; Paul Kreischer of Lightly Treading; Pete Beverly; Paul Reeves of the Partnership for Resource Conservation; Ed Hancock and Greg Barker of Mountain Energy Partnership; Ren Anderson, Admiral Truly, Dan Arvizu, Jessie Harris, Byron Stafford, Kerry Masson, Lee Boughey, Sarah Barba, Jay Burch and Scott Horowitz of NREL; Betsy Petit of Building Science Corporation; Barbara Miller of the National Affordable Housing Network; and Rob Dumont of the Saskatchewan Research Council.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
November 2007

2. REPORT TYPE
Conference paper

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Performance Results from a Cold Climate Case Study for Affordable Zero Energy Homes

5a. CONTRACT NUMBER
DE-AC36-99-GO10337

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
P. Norton and C. Christensen

5d. PROJECT NUMBER
NREL/CP-550-42339

5e. TASK NUMBER
BET78001

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

8. PERFORMING ORGANIZATION REPORT NUMBER
NREL/CP-550-42339

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)
NREL

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 Words)*
The design of this 1280 square foot, 3-bedroom Denver zero energy home carefully combines envelope efficiency, efficient equipment, appliances and lighting, a photovoltaic system, and passive and active solar thermal features to exceed the net zero energy goal. In January 2006, a data acquisition system was installed in the home to monitor its performance over the course of a year. This paper presents full year of energy performance data on the home.

15. SUBJECT TERMS
zero energy home; zeh; photovoltaic; pv; habitat for humanity

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	UL		19b. TELEPHONE NUMBER *(Include area code)*

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

F1147-E(09/2007)